

Balco AB

Balco, technical studies of balcony glazing

- Effect on carbonation and
reinforcement corrosion

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Balco, technical studies of balcony glazing – Effect on carbonation and reinforcement corrosion

1. Introduction

1.1 Description of assignment

Ramböll have been appointed by Balco AB to scientifically show a number of assumed positive effects upon glazing of balconies, including corrosion protection, noise reduction and energy saving. This report deals with the corrosion protection part.

1.2 Information

Upon glazing of balconies important changes occur with regard to corrosion protection. Described below, under each point, are both the changes and their possible effects.

Change	Possible effects (hypotheses)
The facade is screened against direct wind effects and thereby strongly reduces the air change.	This should affect the carbonation rate in concrete.
The facade is screened against direct precipitation.	<p>The humidity load on all concrete is greatly reduced.</p> <p>The relative humidity in concrete decreases which should result in a reduction of the corrosion rate in reinforcement in carbonated concrete.</p> <p>The carbonation rate should increase upon lower relative humidity.</p> <p>The risk of corrosion in other steel constructions and steel sections should reduce.</p>
The air on the balcony is heated up by both the sun's rays and any warming up of the interior house climate.	<p>When the temperature in a glazed balcony rises, the air's humidity in a glazed balcony reduces.</p> <p>The risk of condensation on concrete surfaces should reduce.</p>
The concrete's upper edge may be covered by flooring after glazing.	This provides further protection against carbonation and humidity load.

The above changes indicate a significant effect on the corrosion protection through an altered humidity content in all concrete as well as a change to the corrosion rate in the reinforcement in concrete.

The stated effects of glazing on carbonation and reinforcement corrosion have been studied theoretically in this report in accordance with the following headings:

- A theoretical study of the glazing's effect on the concrete's relative humidity.
- A theoretical study of the glazing's effect on the carbon dioxide's surface concentration and air change.
- A theoretical study of the glazing's effect on reinforcement corrosion on the grounds of (i) altered carbonation rate and (ii) less humidity content in concrete.
- A theoretical comparison of lifespans with regard to reinforcement corrosion in carbonated concrete in a balcony-exposed terrain as well as a glazed balcony.

In this report, the case with and without glazing is studied and it is presumed that the glazing is total. A partly open glazing is of no interest from a corrosion protection perspective.

The theoretical studies should be supplemented by the following measurements over at least 1 year:

- Verification of the glazing's effect on the concrete's relative humidity through sampling and/or in-situ measurements. The air's humidity and temperature shall also be measured in a pair of suitable reference objects.
- Verification of the glazing's effect on the carbon dioxide's surface concentration and air change through measurements in a pair of suitable reference objects.
- Verification of the glazing's effect on the corrosion rate in a pair of suitable reference objects.

To date, no measurements have been carried out, but similar experiments had been carried out in Finland and a short summary of important observations is given in this report.

2. Background regarding carbonation and reinforcement corrosion

2.1 Initiation of reinforcement corrosion through carbonation

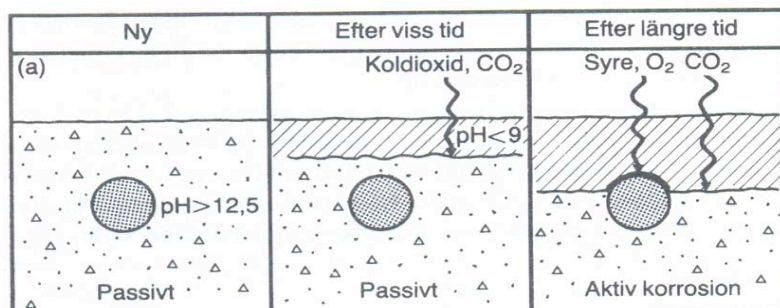
Since, upon cement reactions, alkaline hydroxides are formed, concrete is normally a very alkaline material with a pH value of 13-14. On steel cast into the concrete, a thin membrane of sparingly soluble compounds is formed, which protects the steel from corrosion. This process is termed 'passivation'. Passivation can, however, be broken down and reinforcement corrosion rise when the surrounding concrete's pH value is lowered.

If the concrete is found in an environment where its relative humidity (RH) is within a certain interval, a chemical reaction occurs. Carbon dioxide in the air enters the concrete, breaks up in the humidity present in the capillary pores and forms carbonic acid, which converts the concrete's calcium hydroxide $\text{Ca}(\text{OH})_2$ into calcium carbonate.

This sequence, which is called carbonation, is a quite natural reaction and does not mean that the concrete is worsened in any way. On the other hand, it has the effect of the pH value in concrete being lowered from 13-14 to 7-8.

The penetration of carbon dioxide in concrete is a diffusion process. It is rapid when the concrete is quite dry. But the carbonic acid's reaction does not occur if the concrete is too dry. This is the reason why the most favourable conditions for getting in carbon dioxide correspond to a relative humidity of c. 65%.

Carbonation starts on the surface and then forces its way further and further into the concrete as a front. The concrete has an outer part with low pH and an inner one with high pH. Gradually, the outer part extends so far inwards that it reaches the reinforcement iron, whose passivity is broken down, and if there is then too much humidity present in the concrete, the reinforcement steel starts to corrode, see figure 2.1.



Ny	New
Efter viss tid	After a certain time
Efter längre tid	After a longer time
Koldioxid, CO ₂	Carbon dioxide, CO ₂
Syre, O ₂ CO ₂	Acid, O ₂ , CO ₂
Passivt	Passive
Aktivt korrosion	Active corrosion

Figure 2.1: Carbonation (from Burström, Byggnadsmaterial [Construction material]. 2001).

Carbonation occurs more rapidly on dry surfaces than on damp ones, since the water prevents the carbon dioxide from moving around in the concrete. At the same time, corrosion occurs most rapidly in the most moist environment possible. This means that reinforcement corrosion as a consequence of carbonation occurs most rapidly in an environment where RH lies between 70-100 %.

When the carbonation process is well underway, its rate depends primarily on the concrete's water-cement ratio (wcr). A low wcr means greater density which, in turn, means that it takes longer for the carbonation front to advance.

In order for corrosion to occur, it is necessary for there to be access to acid in addition to access to water. Thereby a dense and well-compacted concrete provides greater protection for the steel than one which is sparse. As a result of corroded steel having a volume which is two to five times greater than a non-corroded steel, tensions occur in the concrete which gradually lead to it cracking and breaking apart. This is known as rust cracking. Reinforcement corrosion also leads to the reinforcement iron's cross-section area reducing, thereby also lowering its bearing strength.

The environment-dependent factors, such as rain, are often difficult to influence while the material dependent factors can be influenced by different choices of concrete compositions and hardening. Binding agents are a major factor for the carbonation rate since the composition of the binding agent determines the volume of material capable of carbonation and also the concrete's density regarding CO_2 . Concrete from Portland cement has a higher content of lime that can be carbonated compared with concrete with additives of fly ash or silica dust, despite this it is difficult to show that the latter carbonates more quickly. Concrete with fly ash and silica dust has a denser structure which makes it harder for CO_2 to force its way in. It is thus difficult to generalise the material influence on carbonation, ([The Concrete Manual – Material] Betonghandboken-Material, 1997).

The water-cement ratio is another important factor that affects the carbonation rate since the density of the concrete strongly depends on the wcr. With a high

wcr there is a poorer density and, at the same time, smaller volumes of matters capable of carbonation are found since the proportion of water is high.

In addition to the covering layer's properties, its thickness is of considerable importance for the time until the carbonation front reaches the reinforcement. A doubling of the cover layer's thickness increases the initiation time by a factor of 4, ([The Concrete Manual – Material]Betonghandboken-Material, 1997).

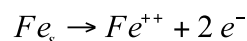
The work procedure for concrete is also a factor of importance for carbonation. It is important to have a cover layer which is as dense and homogenous as possible in order to slow down the process.

2.2 Corrosion of cast reinforcement in carbonated concrete

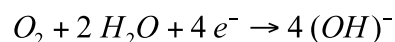
Corrosion can be explained by means of a simple model through charges being transported through an anode and a cathode, which is operated by a potential difference between these. The potential difference depends on various environmental factors which vary by pH, acid content, humidity content, chloride content or combinations of these. Positive metal ions (Fe^{2+}) are released at the anode and react at the cathode with hydroxyl-ions (OH^-) and forms rust ($Fe(OH)_2$). There are two different kinds of corrosion, even corrosion and point corrosion ("pitting"). If the anodic and cathodic services are approximately of equal size, there is an even corrosion. If, on the other hand, the anodic surface is very small in relation to the cathodic, there is pitting instead, which often arises due to chloride concentrations. This form of corrosion is very profound and can lead to serious consequences for reinforced constructions, (Burström, Byggnadsmaterial [Construction material], 2001).

In a carbonated concrete (where the pH value in the pore solution is less than 9) and with access to acid and water, anode and cathode reactions may be presented in the following way.

The equation below shows the release of electrons.

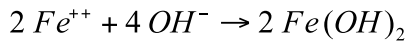


And the cathodic reaction with acid and water as:



The area of the steel surface covered by the passive protection film works as a cathode. Electrons released from the anode are carried through the steel to the cathode surface. The acid diffusion in the concrete pores or from the atmosphere air, catches the incoming electron from the steel and gives rise to a reduction of

the acid in the presence of water and then forms hydroxyl ions. Consequently, the ions dissolved in the pore water then react with the hydroxyl ions and form iron hydroxide



Primary factors for corrosion to start, are:

- Access to acid
- The concrete's humidity
- The concrete's pH value

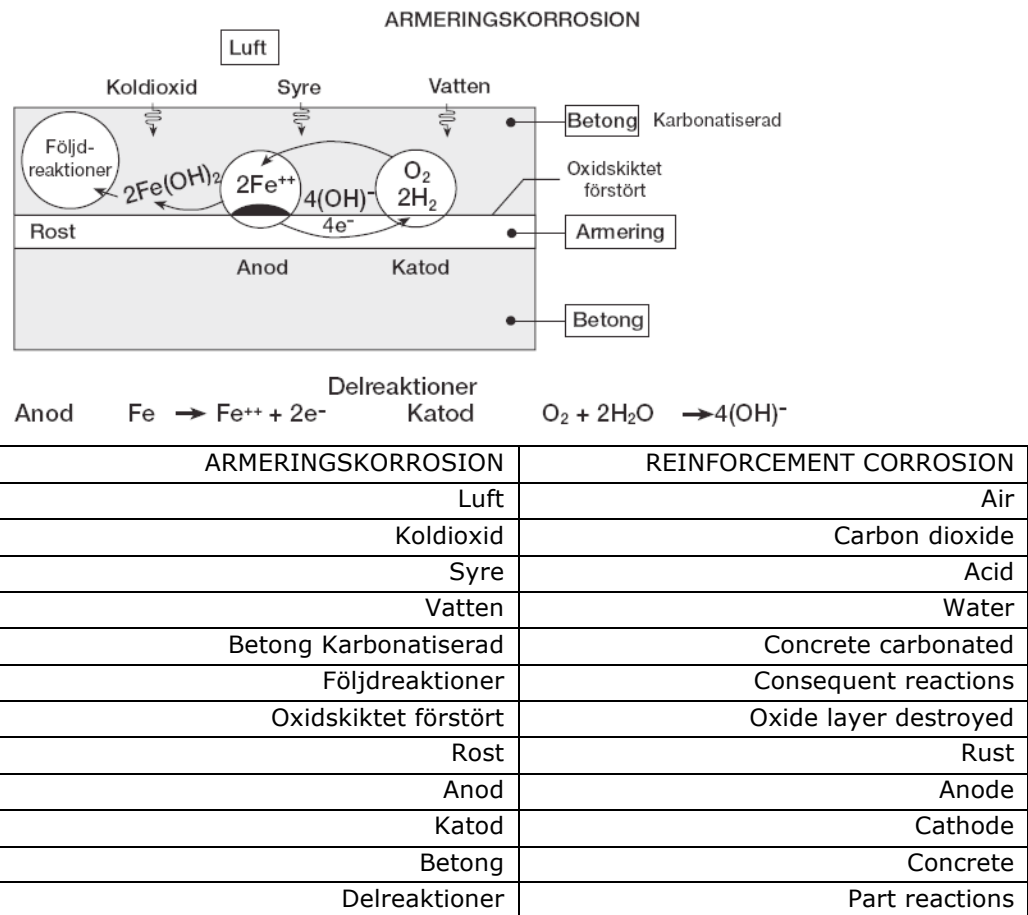


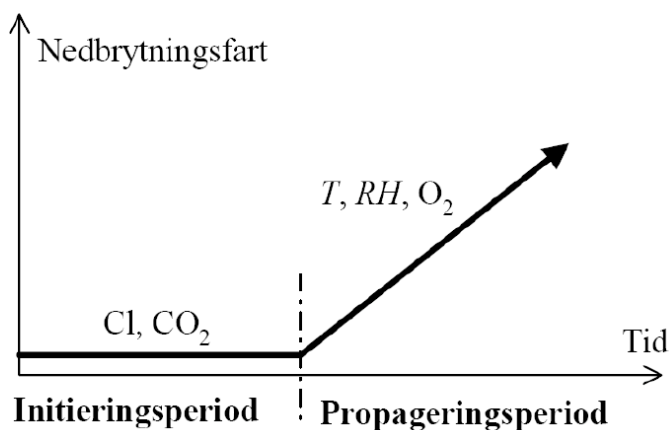
Figure 1.2: Corrosion under the influence of carbonation

The steel in concrete constructions is protected by a covering concrete layer which is very alkaline. This means that corrosion cannot start initially. The corrosion

process can, according to Tuutti (Tuutti, 1982), be divided into an initiating and propagating period. During the initiating period, no corrosion occurs but there are changes happening in the cover layer. The corrosion can start when the front of the carbonating of the cover layer reaches the reinforcement or when the chloride concentration at the reinforcement has reached a critical value, the chloride threshold value. The corrosion period, also known as the propagating period, is relatively short for outdoor constructions, with our climate c. 5-20 years.

Since this time is short, it is necessary to have a longer initiation period and, in that way, achieve a longer lifespan. The length of the initiation period is controlled by a number of factors such as environment, permeability, cement type and wcr (Betonghandboken-Material [The Concrete Manual- Material], 1997).

Another alternative is to alter the conditions for reinforcement corrosion and thereby extend the propagation period. For example, by lowering the concrete's humidity, one can influence the corrosion rate and lifespan, see section 3.



Nedbrytningsfart	Disintegration rate
Initieringsperiode	Initiation period
Propageringsperiode	Propagation period
Tid	Time

Figure 2.3: Corrosion model according to Tuutti (Tuutti, 1982)

3. Effect of glazing on the concrete's relative humidity

One of the most important parameters that enables cast reinforcement to corrode is humidity in the covering concrete layer. The humidity profile in the concrete closest to the concrete surface depends, in turn, on the humidity conditions at the concrete surface.

In the case of a balcony without glazing two humidity sources apply at the concrete surface. The first is water at the concrete surface (humidity film) and is often measured as wet time in hours. The other is surface humidity in the concrete due to the air's relative humidity (RH in %) during the rest of the time when the surface is not wet.

3.1 Wet time

The surface may be exposed to precipitation, surface condensation and/or running water and this is shown through the concept of wet time. The wet time is the time when the construction's surface is wet due to surface condensation, precipitation and water that runs from higher lying parts.

Wet time is not the same as the time that the surface is exposed to precipitation, surface condensation and/or running water. There is a certain displacement in time as the humidity film is not formed immediately when the surface is exposed and the film does not disappear directly the exposure ends. Crucial for the difference between the wet time and the exposure to precipitation etc. is the material's technical humidity properties, e.g. its ability to absorb water.

In figure 3.1 the differences between wet time (defined as a humidity film with a thickness greater than a certain value) and exposure to precipitation (pelting rain) and surface condensation, respectively, are illustrated.

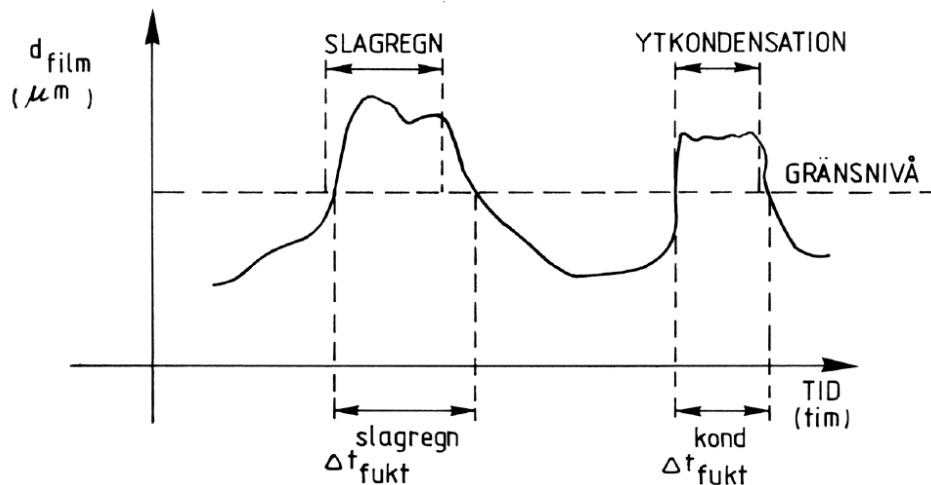


Figure 3.1: The appearance in principle of the differences between humidity loading and wet time for a vertical surface in a porous material, Svennerstedt (1989). (from BFR no. 12, 2007)

Film	Film
SLAGREGN	PELTING RAIN
YTKONDENSATION	SURFACE CONDENSATION

GRÄNSNIVÅ	LIMIT LEVEL
Slagregn	pelting rain
Fukt	humidity
Kond	condensation
Fukt	humidity
TID (tim)	TIME (hours)

According to figure 3.1 the difference between wet time and the time of exposure is greater for pelting rain than for condensation. This is due to the volume of humidity provided is considerably greater with pelting rain than with surface condensation which, in turn, means that the volume of humidity that enters the material will also be greater. The consequence is that the material is sufficiently humid even after it has stopped raining, for a humidity film with a certain thickness to be able to be maintained. The volume of humidity provided through surface condensation is, however, not sufficient for the humidity film to be sufficiently thick for any great length of time.

3.2 Surface humidity

The interplay between the air's RH and the surface's humidity can be calculated in accordance with the following equation.

The humidity conditions on a surface can be described as equivalent surface humidity (RH) and wet time. The equivalent surface humidity can be described as a function of the equivalent surface temperature and of the conditions in the surrounding air, see the equation below (BFR no. 12, Vägledning för livslängdsdimensionering av betongkonstruktioner [Guidelines for lifespan dimensioning of concrete structures], 2007).

$$RF_{\text{surface,equiv}} = \frac{RF_{\text{air}} \cdot v_s(T_{\text{air}})}{v_s(T_{\text{surface,equiv}})} = \frac{v_{\text{air}}}{v_s(T_{\text{surface,equiv}})}$$

$RF_{y_{ta,ekv}}$ is relative humidity at the surface. [%]

RF_{air} is relative humidity in the air. [%]

$v_s(T_{\text{luft}})$ is the saturation vapour content at a certain T_{luft} [g/m³]

$v_s(T_{\text{surface,equiv.}})$ is the saturation vapour content at a certain $T_{y_{ta,ekv}}$ [g/m³]

v_{luft} is the air's vapour content. [g/m³]

Figure 3.2 shows, in a horizontal concrete surface, how a calculated equivalent surface humidity follows the measured air humidity.

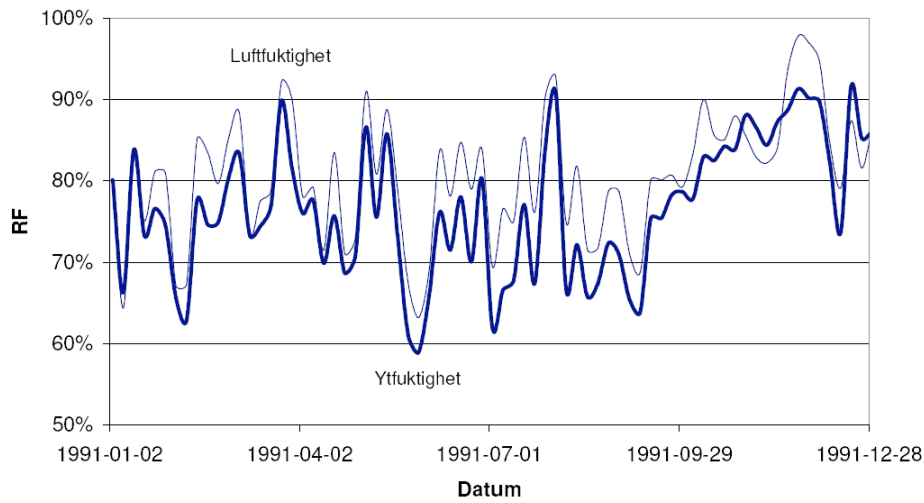


Figure 3.2: Measured air humidities and calculated equivalent surface humidity for a horizontal concrete surface in Holzkirchen (southern Germany) 1991. (mean value for five days). Data from IBP (1995). From BFR no. 12, 2007)

Luftfuktighet	Air humidity
Ytfuktighet	Surface humidity
Datum	Date

From figure 3.2 it is seen that the measured air humidity is generally higher than the calculated equivalent surface humidity. This is due to the equivalent surface temperature often being higher than the air temperature. Higher surface temperatures give rise to a higher saturation vapour content and this means that the quotient $\frac{v_s(T_{\text{luft}})}{v_s(T_{\text{yta,ekv}})}$ becomes less than 1 and the surface humidity $RF_{\text{yta,ekv}}$ is less than the air's relative humidity RF_{luft} .

If the equivalent surface humidity exceeds 100 % RH, i.e. the equivalent surface temperature is lower than the air's dew point, the humidity condensates on the surface. The amount that condensates depends on the difference between the air's vapour content and the saturation vapour content at the surface as well as the material's ability to absorb humidity.

Figure 3.3 shows measured air humidities and calculated equivalent surface humidities for a horizontal concrete surface in Holzkirchen (in southern Germany) (mean value for four hours – two weeks in July 1995).

From figure 3.3 it is seen that the difference between the air and surface humidities is great (four hours mean value). The difference is greatest during sunny days, due to the equivalent surface temperature $T_{\text{yta,ekv}}$ is then

considerably higher than the air temperature, T_{luft} . During nights with considerable radiation, $RF_{\text{yta,ekv}}$ can be greater than 100 %, which means that surface condensation. $T_{\text{yta,ekv}}$ is lower than the day temperature, (BFR no. 12, 2007).

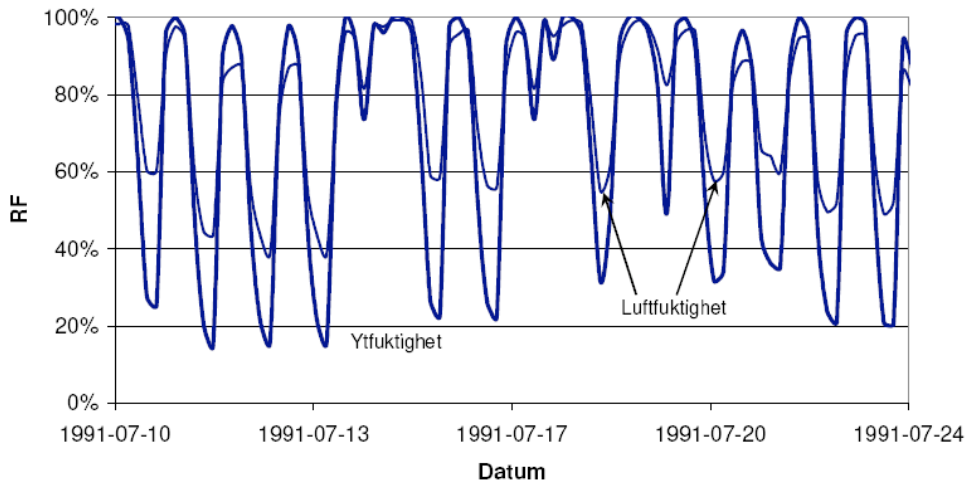


Figure 3.3: Measured air humidities and calculated equivalent surface humidities for a horizontal concrete surface in Holzkirchen (in southern Germany) (mean value for four hours – two weeks in July0. Data from IBP (1995). (From BFR no. 12, Vägledning för livslängdsdimensionering av betongkonstruktioner [Guidelines for lifespan dimensioning of concrete structures], 2007)

Luftfuktighet	Air humidity
Ytfuktighet	Surface humidity
Datum	Date

The variation of $T_{\text{yta,ekv}}$ in relation to T_{luft} is crucial for the risk of surface condensation. It is highly likely that in a glazed balcony the risk of condensation is significantly lower than a balcony without glazing. This is due to $T_{\text{yta,ekv}}$ always going to be greater than T_{luft} due to glazing. This should be charted in a glazed balcony through humidity and temperature measurements.

3.3 Humidity profile in concrete

The concrete's surface humidity and wet time as well as their variations, give rise to a response described by the concrete's humidity state. This varies with the depth and time, depending on the surface humidity' and wet time's extent and variations, and can be determined by the laws governing conservation of materials and energy.

Given here is an example of how the humidity state can look in one dimension (1D) depending upon the marginal conditions. Information about how the humidity state can be determined in purely practical terms is to be found in DuraCrete (1999), (BFR no. 12, 2007).

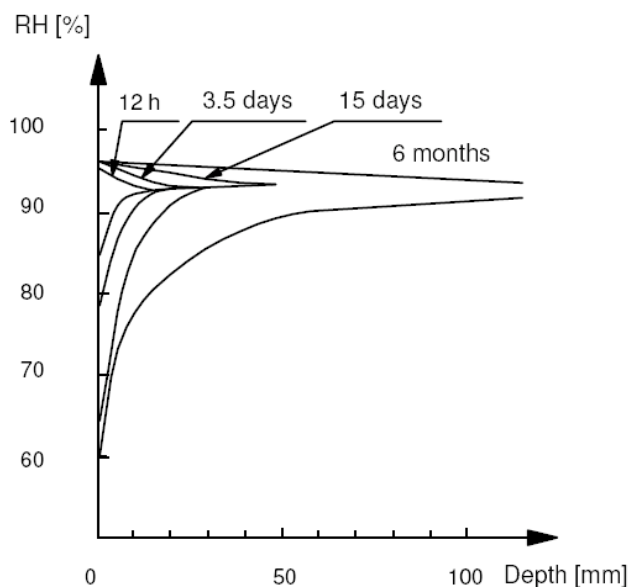


Figure 3.4: Calculated humidity profiles in concrete exposed to cyclical humidity loadings. Arfvidsson & Hedenblad (1991). (from BFR no. 12, Vägledning för livslängdsdimensionering av betongkonstruktioner, [Guidelines for lifespan dimensioning of concrete structures] 2007)

In general the humidity state is altered significantly slower than the temperature state. This is seen from figure 3.4, where changes in the humidity loadings at the surface are noted at a depth of c. 30 mm only after 2 weeks' exposure, and at 100 mm after 6 months.

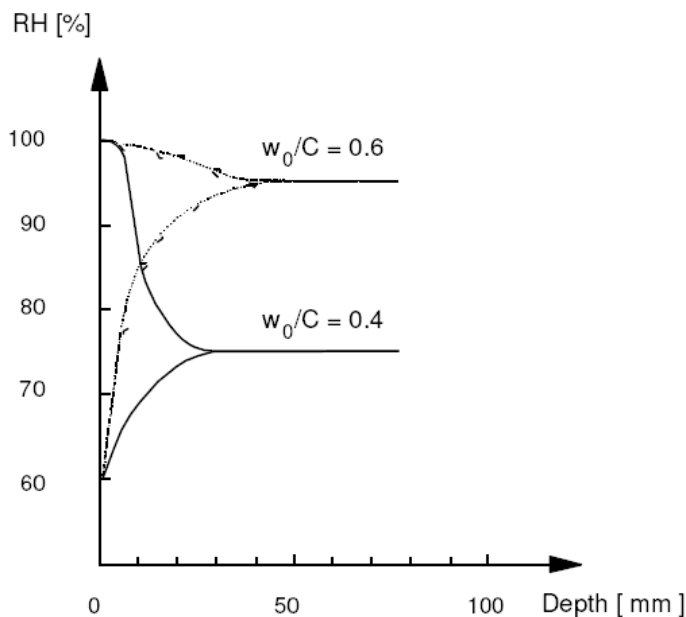


Figure 3.5: Calculated humidity profiles in concrete with different compositions, exposed to cyclical humidity loadings. Arfvidsson & Hedenblad (1991).

The water-cement ratio is defined and shown as the Quotient w_0/C and influences the time for drying out and humidification. The humidity state at a greater depth is relatively constant, but if influenced by the concrete composition and w_0/C as is seen in figure 3.5.

3.4 Effect of glazing on surface humidity and wet time

The probable effects of glazing on reinforcement corrosion arise due to altered humidity conditions in concrete slabs and surrounding air. If the concrete surface is kept dry over a certain period the concrete's humidity at the reinforcement level will reduce and thereby lessen the possibility of corrosion during the propagation phase.

The wet time due to precipitation and running water, is almost zero.

The wet time due to surface condensation reduces sharply. this is due to both the air temperature and, first and foremost, the concrete surface's temperature, going to be higher in a glazed balcony. Through measuring the air and concrete's temperature and humidity, one can determine the reduction of wet time in hours due to surface condensation.

The interior air's humidity (in comparison with the exterior air's humidity) reduces and thus the surface humidity reduces due to glazing. The extent to which the surface humidity reduces depends on the heating up of the interior air caused by

sunshine and convection (heating up of interior air). [Translator's note: Should this be 'convection'??]

4. Effect of glazing on the carbon dioxide's surface concentration and air change

The characteristic carbon dioxide concentration in free air up to a concrete surface is around $5.0 \cdot 10^{-4}$ kg/m³ (per m³ air). It has, however, increased sharply in recent years and long-term forecasts indicate values up to $8.0 \cdot 10^{-4}$ kg/m³ in a one hundred year perspective, (BFR no. 12, 2007).

For concrete surfaces inside more or less enclosed spaces, the carbon dioxide concentrations are lower due to the concrete surfaces consuming the air's carbon dioxide. how much lower the concentration will be depends on how great the air change is in these spaces and how great the consumption of carbon dioxide is, i.e. the concrete composition, micro-climate and how deep the carbonation has already gone.

It is highly likely that glazing of balcony spaces contributes towards a lower air change at concrete surfaces. Air change and carbon dioxide concentration should be measured in balconies with and without glazing with the aim of establishing any differences. Without accurate measurements it is difficult to determine the effect of glazing on air change and the air's CO_2 concentration at concrete surfaces.

5. Effect of glazing on carbonation

Carbonation occurs when carbon dioxide from the air enters the concrete and reacts with calcium hydroxide. A carbonation front is formed which gradually penetrates deeper into the concrete giving rise to a sharp lowering of the pH-value in the concrete. Corrosion can begin when the carbonation front has reached the reinforcement.

The rate of the carbonation from is determined by the surrounding CO_2 concentration, the concrete's ability to absorb CO_2 and the diffusion rate for CO_2 .

Since concrete is not a homogenous material the carbonation progresses at different rates in the cross-section. An average is therefore suitably calculated for the carbonation.

A simple calculation model for the carbonation front i.e. the carbonation depth, can be described in the following manner (4):

$$x = k \sqrt{t}$$

where

x is the carbonation depth

k is the coefficient

t is time

The value of the coefficient (k) can be theoretically calculated if one knows the concrete's diffusion coefficient for CO_2 , the concrete's CO_2 -absorption as well as the surrounding CO_2 -concentration.

The carbonation process is relatively complicated if one takes into consideration all important part-processes under actual climactic conditions. Where balcony slabs without glazing are concerned, the cover layer's humidity conditions normally vary during different periods of the year and are strongly affected by rain which hits the concrete surface. The humidity variations in concrete are as shown in figure 5.1, (BFR no. 12, 2007).

Diffusions of carbon dioxide shall therefore occur periodically through a relatively humid cover layer with high diffusion resistance, different at different depths. In other periods, the cover layer is relatively dry and the diffusion resistance is then considerably lower, especially closest to the dry surface. The part of the concrete which is carbonated has, however, other humidity-binding properties than the concrete which is further in, (BFR no. 12, 2007).

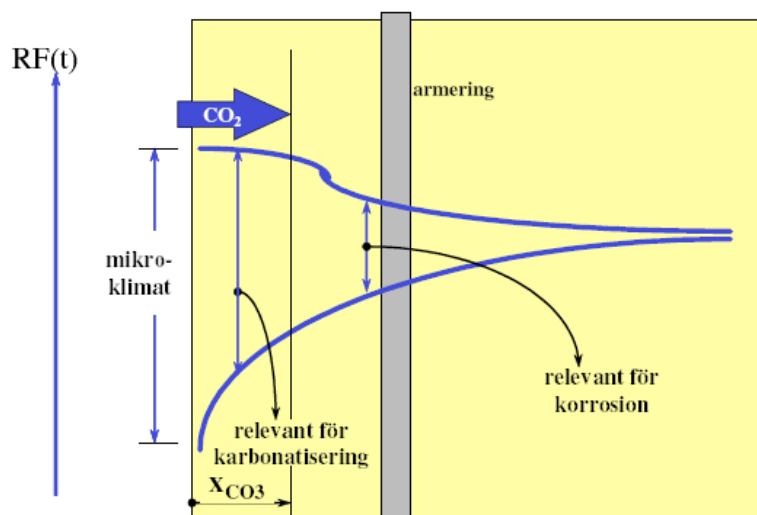


Figure 5.1: The effect of humidity variations on the initiation of reinforcement corrosion by carbonation, (BFR no. 12, 2007).

mikroklimat	micro-climate
armering	Reinforcement
relevant för karbonisering	relevant to carbonation
relevant för korrosion	relevant to corrosion

Carbon dioxide shall react with the greater part of the volume of lime capable of carbonation before it can penetrate further. How much this is depends, for example, on the humidity level and the age of the concrete.

A correct description of all these aspects requires a complicated computer model. Such a "micro-model" was developed by CEB (1997), but is primarily used for quantifying the parameters in simpler "meso-models". The models, according to DuraCrete (1998) for initiation of reinforcement corrosion due to carbonation, are the same as the "meso-model" according to CEB (1997), (BFR no. 12, 2007).

The carbonation rate is affected by a number of material and environment-dependent factors as stated above. The surrounding environment affects the humidity condition of the cover layer. In dry concrete there is little or very slow carbonation since it requires a certain access to humidity. A maximum carbonation occurs when the humidity is favourable, 50-60 % RH. If the relative humidity is higher and approaches saturation, i.e. when RH is 100 %, the carbonation becomes slow or non-existent. At such high relative humidity the carbon dioxide which drives the carbonation has difficulty in penetrating through the water.

Figure 5.2 shows carbonation depth as a function of time in different parts of one and the same construction, from CEB (1997).

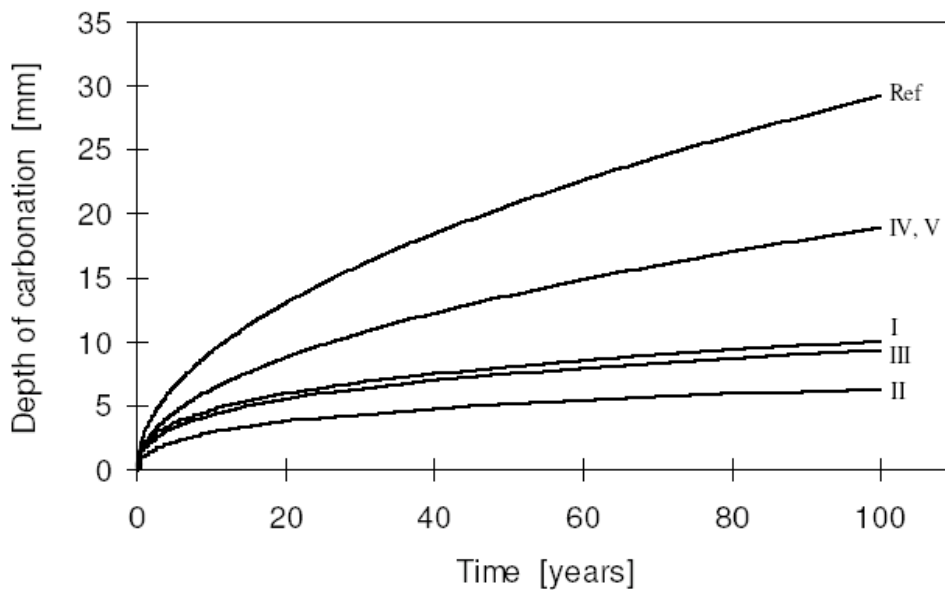
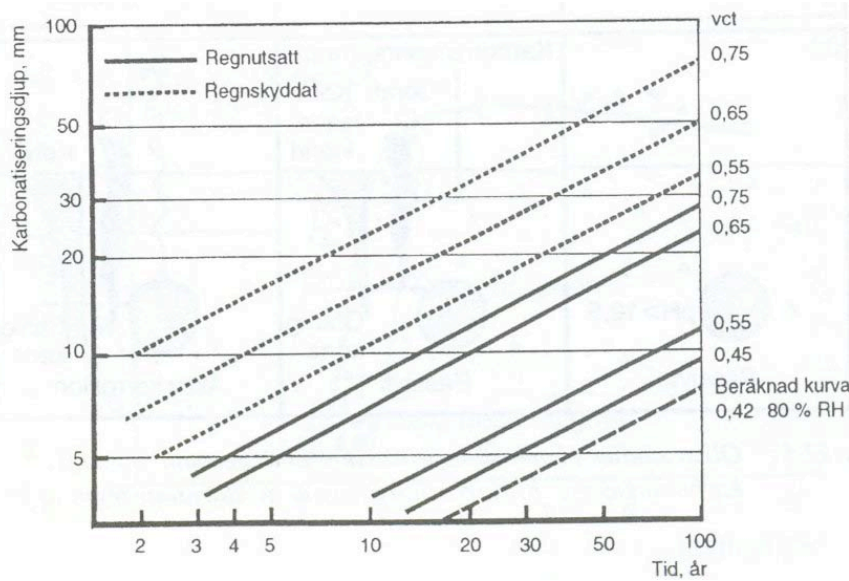


Figure 5.2. Carbonation depth as a function of time in different parts IV of one and the same construction, i.e. different values for n, k1 and k2, CEB (1997).

Reference is indoor climate,
 I-III are different parts exposed to rain
 IV & V are protected against rain.

Constructions exposed to rain have been seen to have a lower carbonation rate compared with those protected from the rain, see also figure 5.3,



Karbonatiseringsdjup mm	Carbonisation depth, mm
Regnutsatt	Exposed to rain
Regnskyddat	Protected from rain
Berkäknad kurva	calculated curve
Tid, år	Time, year

Figure 5.3: Carbonation depth for rain-exposed and rain-protected constructions, respectively ([The Concrete Manual – Material] Betonghandboken-Material, 1997).

Therefore differences in carbonation rate in figures 5.2 and 5.3 are due to differences in the concrete’s humidity content. Diffusion of carbon dioxide in the concrete’s capillary pores is due to the humidity content in capillary pores and the humidity-dependence is considerable. Relative humidity (RH) in the concrete’s cover layer directly affects the resistance to diffusion of carbon dioxide and, thereby, directly the initiation time for reinforcement corrosion. Humidity-dependence is shown in the figure 5.4 below, (BFR no. 12, 2007).

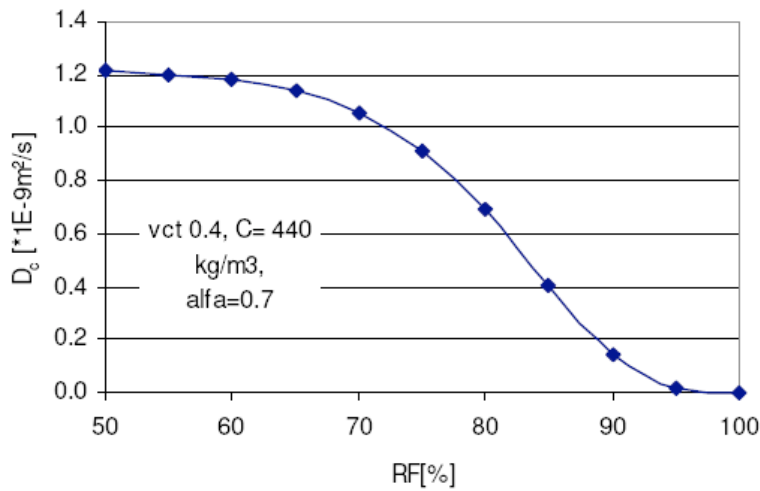


Figure 5.4: Humidity-dependence in the diffusion coefficient for carbon dioxide, according to DuraCrete (Duracrete, 1998), (BFR no. 12, 2007).

The diffusion coefficient is higher and almost constant between RH corresponding to 50 and 70 %. Between 70 and 90, the diffusion coefficient falls off. For RH higher than 90 %, the diffusion coefficient is almost negligible.

It is highly likely that, after glazing of balcony slabs (glazing above and below the slab) the concrete's relative humidity is lowered at the surface and thereafter RH is affected directed further into the cover layer. It is probable that the RH in the concrete, after glazing, is lowered from a level above 90 % to a level between 70 and 80 %. This means a higher diffusion coefficient and thus a higher carbonation rate. In order to clarify the humidity variation in balcony slabs after glazing, humidity measurements should be made in reference objects with and without glazing.

6. Effect of glazing on reinforcement corrosion

The principal function for balcony glazing in the Nordic climate is to keep rainwater, snow and dust away from a balcony and the heat in. It is clear that balcony glazing does not affect humidity exposure only by preventing humidity penetrating the balcony, but also by creating such a micro-climate that promotes drying. The sun radiation as well as the thermal flow through the outer wall or a window behind the balcony probably raises the temperature inside the balcony, which increases the measurement deficit and will probably lower the humidity content of the concrete still further.

As seen in figure 6.1, when the humidity in the concrete (at reinforcement level) lies below 90 % RH, the corrosion rate reduces by 90 % (Tuutti 1982). Where the potential acceleration of carbonation on the grounds of the concrete's drying out is concerned (Parrott 1987), the rise is only 10-20 %. Also earlier experiences regarding repair of balconies show that corrosion due to carbonation usually occurs where the humidity loading is highest, but not where opposite conditions apply.

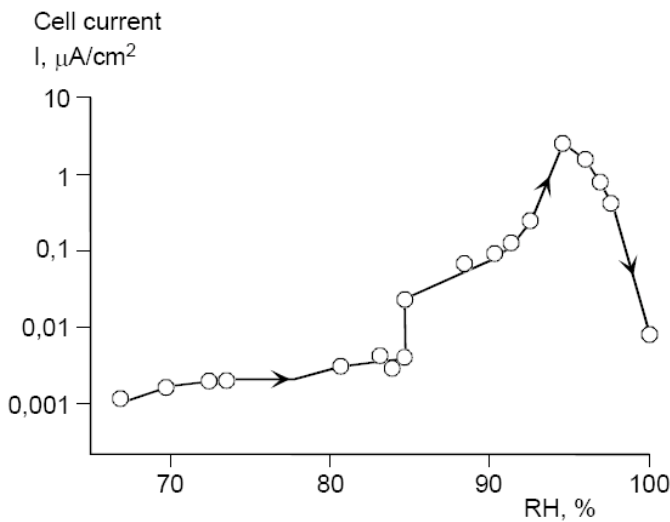


Figure 6.1: The connection between the concrete's RH and the corrosion flow according to Tuutti (Tuutti, 1982).

To summarise, glazing means a drier concrete surface, less humidity in concrete and lower corrosion rate of reinforcement iron in carbonated concrete. This is the most advantageous effect of glazing of balconies for corrosion protection. In order to illustrate the humidity variation in concrete slabs before and after glazing, humidity measurements should be taken in reference objects with and without glazing.

7. Effect of glazing on the lifespan of concrete constructions

One of the most common causes of the initiation of corrosion is carbonation. Corrosion of reinforcement often limits the lifespan of concrete constructions. Normally, the lifespan is divided into an initiation period (the time it takes before the reinforcement starts to corrode) and a propagation period (the time it takes before the maximum allowed corrosion has been reached), see figure 7.1.

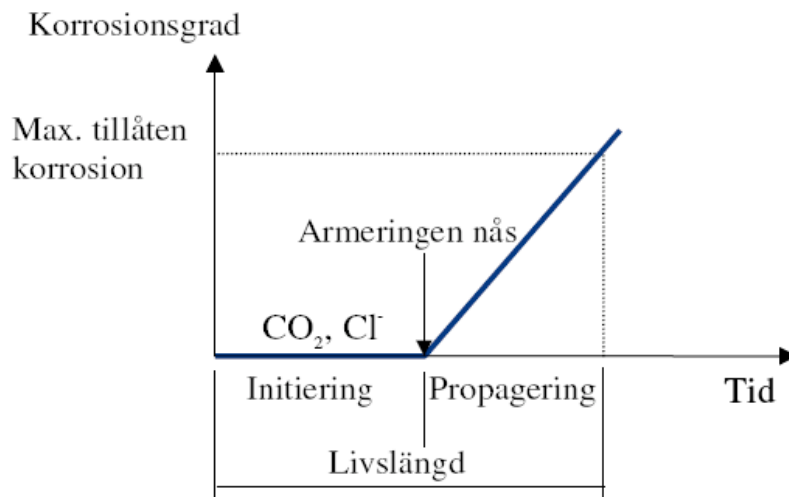
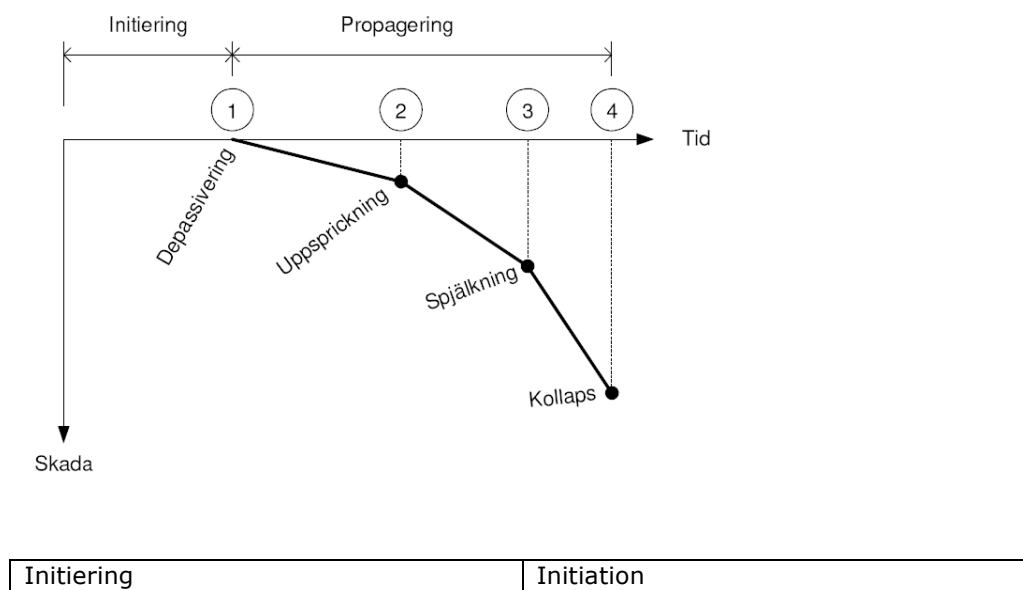


Figure 7.1: Corrosion model according to Tuutti (Tuutti, 1982)

Maximum permitted corrosion is often set at the degree of corrosion that causes splitting in the covering concrete layer in the concrete, i.e. point 3 in figure 7.2, (BFR no. 12, 2007).



Propagering	Propagation
Depassivering	Depassivation
Uppspritning	Cracking up
Spjälkning	Splitting
Kollaps	Collapse
Tid	Time

Figure 7.2: Illustration of different events in connection with reinforcement corrosion.

Upon calculation of the concrete construction's lifespan, one may choose between only using the initiation period or allowing a degree of corrosion.

By means of models showing how rapidly carbon dioxide penetrates the cover layer, one can determine how long the initiation period is, see annexe A. By means of models describing corrosion rate and maximum permitted corrosion, the propagation time can be determined, see annexe B.

7.1 Calculation of propagation time (with and without glazing)

Calculations are made in accordance with calculation models in annexe B. Here the propagation period is calculated as number of years until the relevant crack width (corresponding to 1.0 mm) which is assumed to cause splitting. The criterion for splitting of the covering concrete layer is set at 1.0 according to Duracrete, (BFR no. 12, 2007).

The propagation period is calculated for the following cases:

1. balcony slab without glazing (unprotected)
2. balcony slab with glazing (protected)

The balcony slab in this calculation is a reinforced concrete slab with 20 mm in covering concrete layer and a breaking strain corresponding to 2 MPa. The reinforcement in the upper edge is 16 mm in diameter. Here the lifespan is defined as the sum of the initiation and propagation time for reinforcement corrosion.

Calculation time for unprotected balcony, case 1:

The calculation follows models according to Duracrete, (BFR no. 12, 2007) in annexe B. Parameters for calculation of resistivity:

$$\rho_0^k = 57 \quad \Omega\text{m, potential electrolytic resistivity}$$

$$t_{hydr} = 1 \quad \text{years, concrete's age, though maximum 1 year}$$

$n_{res}^k = 0,23$	exponent for time dependence
$k_{c,res}^k = 1,0$	hardening factor
$k_{RH,res}^k = 1,08$	humidity factor, applies to RH = 90 %
$k_{cl,res}^k = 1,0$	chloride factor
$T = 10$	°C, average temperature, given conditions
$k^k = 0,025$	°C ⁻¹ , factor for temperature dependence

The resistivity's temperature factor is calculated according to the following equation:

$$k_{T,res}^k = (1 + K^k (T - 20))^{-1} = (1 + 0,0025 (10 - 20))^{-1} = 1,33 \text{ °C}^{-1}$$

Resistivity according to the equation below:

$$\rho^k = \rho_0^k \cdot \left(\frac{t_{hydr}}{t_0} \right)^{n_{res}^k} \cdot k_{c,res}^k \cdot k_{T,res}^k \cdot k_{RH,res}^k \cdot k_{cl,res}^k$$

$$\rho^k = 57 \cdot \left(\frac{365}{28} \right)^{0,23} \cdot 1,0 \cdot 1,33 \cdot 1,08 \cdot 1,0 = 148 \text{ } \mu\text{m}$$

Parameter for calculation of corrosion rate:

$m_0 = 882$	$\mu\text{m} \cdot \Omega\text{m}/\text{year}$, constant
$F_{cl}^k = 1,0$	factor for chloride corrosion rate
$\alpha^k = 2,0$	factor for possible pitting
$\gamma_v = 1,0$	partial coefficient for corrosion rate

$$V^d = \frac{m_0}{\rho^k} \alpha^k F_{cl}^k \gamma_v = \frac{882}{147} \cdot 2,0 \cdot 1,0 \cdot 1,0 = 11,9 \text{ } \mu\text{m}/\text{year}$$

For calculation of rust attack depth, the relative length of wet periods is assumed to be $w_t = 0,75$. The rust attack depth will then be according to the following equation:

$$P^d = V^d w_t (t - t_i^d) = 11,9 \cdot 0,75 \cdot (48 - 30) = 161 \text{ } \mu\text{m}$$

The rust attack depth needed for initiating a crack is in accordance with the following equation with the value of regression coefficients according to annexe B:

$$p_0^d = a_1 + a_2 \frac{x^d}{d} + a_3 f_{c,sp}^d = 74,4 + 7,3 \cdot \frac{20-0}{16} - 17,4 \cdot 2,0 = 48,7 \quad \mu\text{m}$$

Crack breadth according to the following equation with parameters according to annexe 2:

$$w^d = w_0 + b^d (p^d - p_0^d) = w_0 + \gamma_b b^k (p^d - p_0^d)$$

$$w^d = 0,050 + 0,0886 \cdot (161 - 48,7) = 1,01 \quad \text{mm}$$

It is presumed that corrosion started after 30 years when the carbonating front reaches the reinforcement. It then takes a further 19 years for the corrosion to cause splitting of the cover layer in the upper edge reinforcement, i.e. a crack width corresponding to 1 mm.

Calculation time for protected balcony, case 2:

The calculation follows models according to Duracrete, (BFR no. 12, 2007) in annexe B. Parameters for calculation of resistivity:

$$\rho_0^k = 57 \quad \Omega\text{m, potential electrolytic resistivity according to testing}$$

$$t_{hydr} = 1 \quad \text{years, concrete's age, though maximum 1 year}$$

$$n_{res}^k = 0,23 \quad \text{exponent for time dependence}$$

$$k_{c,res}^k = 1,0 \quad \text{hardening factor}$$

$$k_{RH,res}^k = 3,18 \quad \text{humidity factor, applies to } RH \leq 80 \%$$

$$k_{cl,res}^k = 1,0 \quad \text{chloride factor}$$

$$T = 15 \quad ^\circ\text{C, average temperature, given conditions}$$

$$k^k = 0,025 \quad ^\circ\text{C}^{-1}, \text{ factor for temperature dependence}$$

The resistivity's temperature factor is calculated according to the following equation:

$$k_{T,res}^k = (1 + K^k (T - 20))^{-1} = (1 + 0,0025 (15 - 20))^{-1} = 1,14 \quad ^\circ\text{C}^{-1}$$

Resistivity according to the equation below:

$$\rho^k = \rho_0^k \cdot \left(\frac{t_{hydr}}{t_0} \right)^{n_{res}^k} \cdot k_{c,res}^k \cdot k_{T,res}^k \cdot k_{RH,res}^k \cdot k_{cl,res}^k$$

$$\rho^k = 57 \cdot \left(\frac{365}{28}\right)^{0,23} \cdot 1,0 \cdot 1,14 \cdot 3,18 \cdot 1,0 = 374 \text{ } \mu\text{m}$$

Parameter for calculation of corrosion rate:

$m_0 = 882$	$\mu\text{m}\cdot\Omega\text{m}/\text{year}$, constant
$F_{cl}^k = 1,0$	factor for chloride corrosion rate
$\alpha^k = 2,0$	factor for possible pitting
$\gamma_v = 1,0$	partial coefficient for corrosion rate

$$V^d = \frac{m_0}{\rho^k} \alpha^k F_{cl}^k \gamma_v = \frac{882}{314} \cdot 2,0 \cdot 1,0 \cdot 1,0 = 4,7 \text{ } \mu\text{m}/\text{year}$$

For calculation of rust attack depth the relative length of wet periods is assumed to be $w_t = 0.5$. The rust attack depth will then be according to the following equation:

$$P^d = V^d w_t (t - t_i^d) = 4,7 \cdot 0,5 \cdot (98 - 30) = 160 \text{ } \mu\text{m}$$

The rust attack depth needed to initiate a crack is according to the following equation with the value of regression coefficients according to annexe 2:

$$p_0^d = a_1 + a_2 \frac{x^d}{d} + a_3 f_{c,sp}^d = 74,4 + 7,3 \cdot \frac{20 - 0}{16} - 17,4 \cdot 2,0 = 48,7 \text{ } \mu\text{m}$$

Crack breadth according to the following equation with parameters according to annexe B:

$$w^d = w_0 + b^d (p^d - p_0^d) = w_0 + \gamma_b b^k (p^d - p_0^d)$$

$$w^d = 0,050 + 0,0886 \cdot (170 - 48,7) = 1,01 \text{ } \text{mm}$$

It is assumed here that corrosion starts after 30 years when the carbonating front reaches reinforcement. It then takes a further 68 years when the corrosion causes splitting in the upper edge reinforcement, i.e. a crack breadth corresponding to 1 mm.

Comparison of propagation periods (cases 1 and 2):

A comparison of the propagation periods (corrosion that causes cover layer splitting) in reinforcement iron in an already carbonated concrete slab in a balcony, with and without glazing, shows the positive effect of glazing on lifespan.

Table 7.1 shows the effect of glazing on propagation period for balcony slabs

Balcony	Concrete's average humidity RH [%]	Initiation period, [year]	Propagation period, [year]	Lifespan [year]
Unprotected	> 90	30	18	48
Protected	< 80	30	68	98
Differences	> 10	0	50	50

It is here assumed that glazing is done after 30 years when the entire covering concrete layer is carbonated and the corrosion started after 30 years when the carbonating front reaches the reinforcement. But because of lower humidity content in glazed balcony slabs, it takes considerably longer time, i.e. 68 years, before the corrosion causes splitting of the cover layer in the upper edge reinforcement (i.e. a crack breadth corresponding to 1 mm). Corresponding propagating period for balcony slabs without glazing has been calculated at 18 years. This means that glazing has extending the propagating phase, i.e. the theoretical corrosion time, by c. $68 - 18 = 50$ years.

8. Effect of glazing on frost damage in concrete

In Sweden, the most important disintegration mechanisms for lifespan projection of new concrete constructions are frost and reinforcement corrosion.

Frost damage in concrete constructions constitutes two totally different types: interior frost damage from freezing in clean water and frost descaling upon freezing in a salt-containing environment.

8.1 Interior frost damage from freezing in clean water

Where balconies are concerned, frost damage often relates to freezing in clean water. Part of the water in the concrete's pore system is bound so strongly that it cannot freeze other than at very low temperatures. The other pore water is "freezable water" which expands in connection with freezing into ice. The expansion provides a sharp increase in the pore water pressure, a "hydraulic pressure", which can split the material apart. The crucial factor for whether this occurs or not is how large a part of the accessible pore system is filled with water. This is expressed by the water saturation degree, S .

The water saturation degree which indicates the limit at which frost damage occurs in connection with freezing is the "critical water saturation degree" S_{kr} . This is a material property that can be determined through a testing procedure. It isn't

completely constant but reduces somewhat with freezing temperature, $S_{kr(T)}$. The risk of occurrence of an interior frost damage is, consequently, connected to the probability with which the "relevant water saturation degree" S_{akt} exceeds the critical, $S_{kr(T)}$, at the same time as the concrete freezes.

How great S_{akt} becomes in a concrete construction is a humidity mechanical problem. It depends on the concrete's humidity mechanical properties, the air pore system's structure and how the micro-climate on the concrete surface varies with time.

Concrete surfaces exposed to water fairly quickly achieve an actual water saturation degree that corresponds to the breaking point, "knickpunkten" ["cracking point"]. After that, the humidification occurs very slowly. Constructions that are in constant contact with water have a constantly increasing water saturation degree in time, as more and more of the air pore system is filled with water. The time perspective of this is, however, months, years, decades and even centuries!

The consequence of S_{akt} being greater than $S_{kr(T)}$ when the concrete freezes is local frost damage in the area where $S_{akt} > S_{kr(T)}$. This gives rise to a local, sharp worsening of the concrete resistance and stiffness. If the extent is great, an interior frost cracking can cause cracks or breaking loose of the surface layer.

It is highly probable that a glazed balcony reduces the relevant water saturation degree in relation to the critical water saturation degree when the balcony is protected against humidity and rain. The risk of frost damage should be reduced. In order to chart this, humidity measurements should be taken in reference objects with and without glazing.

9. Measurements carried out in Finland

9.1 Introduction

In Finland J.S. Mattila at Tampere University as carried out measurements of corrosion rates on sample bodies in balconies with and without glazing. In this section the most important measurements, observations and conclusions from the investigations carried out by Mattila in Finland, are reproduced (Mattila, 2003).

According to Mattila the evaluation of the efficiency of balcony glazing in lowering humidity loading and water content in concrete constructions is a complicated problem. This influence is clearly seen as being positive, but it is impossible to assess quantitatively without measurement data from the field. A potential way of assessing the effect of balcony glazing on the humidity content of concrete is to monitor it by means of electronic equipment. This is, however, a scientifically

unsound method for two reasons. Firstly the accuracy of electronic humidity measurement is not particularly high. For example the corrosion rate during a decade in carbonated concrete can be less than the measurement part's sensitivity. The humidity meters that are employed work best on the hygroscopic area only, while corrosion is known to be fastest in partly saturated concrete, i.e. at the super-hygroscopic interval (Alonso et al, 1988). Because of this humidity measuring is not a reliable way in which to study the effect of glazing on corrosion, unless the reduction of the humidity content is systematic and very large, (Mattila, 2003).

One way of circumventing the problem of humidity measurement is to measure the degree of the actual corrosion. The corrosion rate in cast steel rods in carbonated concrete can be checked relatively simply, e.g. through the polarisation resistance method (Stern & Geary 1957). It is a sensible way of obtaining a quantitative picture of the protective effects of balcony glazing since the corrosion is controlled primarily by surrounding humidity and temperature.

9.2 Measurements carried out and results

A tailor-made piece of equipment for monitoring corrosion rates for steel in concrete has been developed for this purpose. The unit employs the polarisation resistance technique in order to measure the momentary corrosion rate (Stern & Geary 1957). The cumulative corrosion attack can easily be calculated from gathered data. The unit employs modern data technology so that the steel's electrical potential is directly controlled by a computer. The apparatus is fully automatic in carrying out continuous monitoring of corrosion and is equipped with a mobile data connection in order to gather data from the field. The unit can deal with a maximum of 120 measurement channels and is described in greater detail in (Mattila 2003).

An important point to consider is that the information should be gathered from the field where all parameters are determined by a micro-climate inside a balcony, which determines the degree of disintegration.

For monitoring purposes special sensors were prepared and fitted in balconies on existing buildings. The sensors contain reinforcement iron and suitable electrodes for monitoring the corrosion rate of polarisation resistance.

The effectiveness of balcony glazing in reducing corrosion is evaluated through monitoring the corrosion rate that reinforcement iron has in carbonated concrete, both glazed and open balconies. What the monitoring system measures is the momentary corrosion flow [$\mu\text{A}/\text{cm}^2$]. By means of the momentary corrosion flow it is possible to calculate the cumulative radius loss of the steel in μm (i.e. deep corrosion attack) by integrating the corrosion flow over time and applying Faraday's Law.

The cumulative radius loss over 25 months of monitoring is shown in figure 9.1. The results were very much alike in all three investigated buildings.

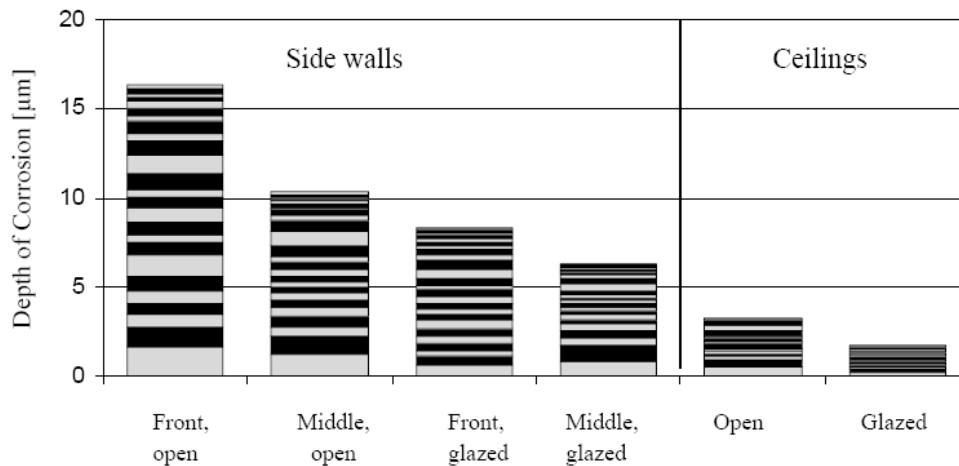


Figure 9.1. Average cumulative radius losses in the steel in three buildings over 25 months (from Mattila 2003)

The parts in each column in the figure represent the monthly values of the radius loss whereby the lower part of each column represents a radius loss measured in the first monitored month, i.e. December 2000, and the upper part is the last monitored month, i.e. December 2002.

Fig. 9.1 shows that balcony glazing reduced the corrosion rate for steel in concrete clearly and systematically. The decrease during the follow-up period was about 30 to 50 % in the side walls and 50 % in slabs. For evaluating measured volumes (radius losses), the result from Alonso et al 1998, Andrade et al 1993 can be used as a guideline. According to these an average radius loss of 50 µm is what is required in order to cause the first visible cracks (0.05-0.1 mm). On the basis of this it is possible to make a rough calculation of the duration of the active corrosion prior to the forming of cracks in studied structures. The result of this calculation is presented in table 9.1.

Table 9.1. Average annual corrosion depth and calculated duration of the active corrosion in glazed and open balconies (from Mattila 2003)

	Balcony side walls		Ceiling surfaces	
	Glazed	Open	Glazed	Open
Average yearly corrosion depth during the monitoring period [µm]	4	7	1	2
Calculated duration of the active corrosion [a]	12	7	50	25

Table 9.1 shows that increased lifespan of the structures can be significant. It is worth noting in particular the low corrosion rate in roof surfaces. The calculated

time for active corrosion prior to cracking will be about 25 years in open balconies and this can be doubled by glazing. The result shows that glazed balconies can enjoy decades of remaining lifespan without major repair measures.

The temperature in concrete was also checked once an hour at the same places where the corrosion was measured. The measured temperatures were processed into average figures per month for glazed and open balconies. The monthly differences in the temperatures between glazed and open balconies are shown in Figure 9.2. The positive difference shows that the temperature was higher in the glazed balconies.

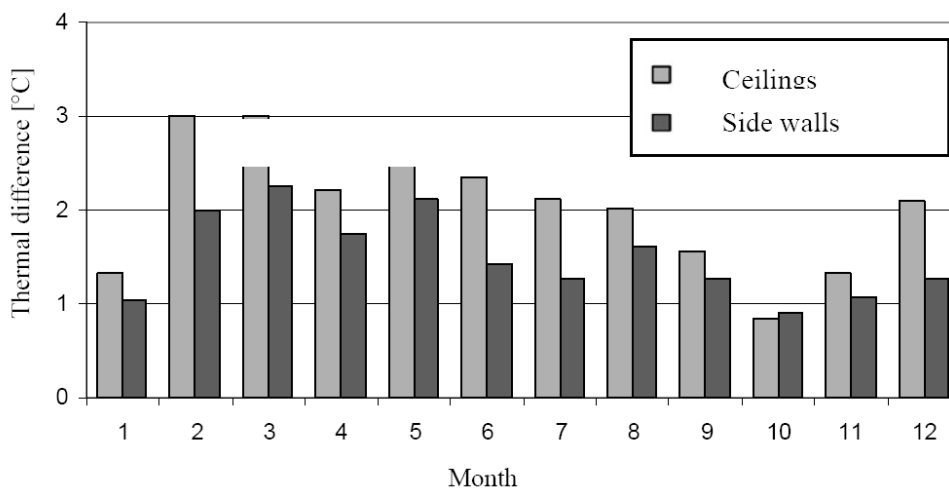


Figure 9.2. The difference in monthly average temperatures in concrete in glazed and open balconies. The positive difference is the situation where the temperature has been higher in the glazed balconies (from Mattila 2003)

From average temperatures in concrete in figure 9.2, it is seen that the temperature is systematically higher in glazed balconies. In half the height of side walls the temperatures were, on the average, c. 1.5 °C and, in the roof, on the average, c. 2 °C higher in glazed balconies compared with open balconies. This temperature difference also applied during the cold time of the year when the sun's rays are very weak. This shows that small differences in temperature can be regarded as being important since they increase the saturation's deficit and thereby promote drying of concrete.

In order to assess the risk of frost damage on the basis of corrosion rate, all measurements of corrosion rates are shown as a function of temperature in concrete at the time of the corrosion rate measurement. This is shown in figure 9.3.

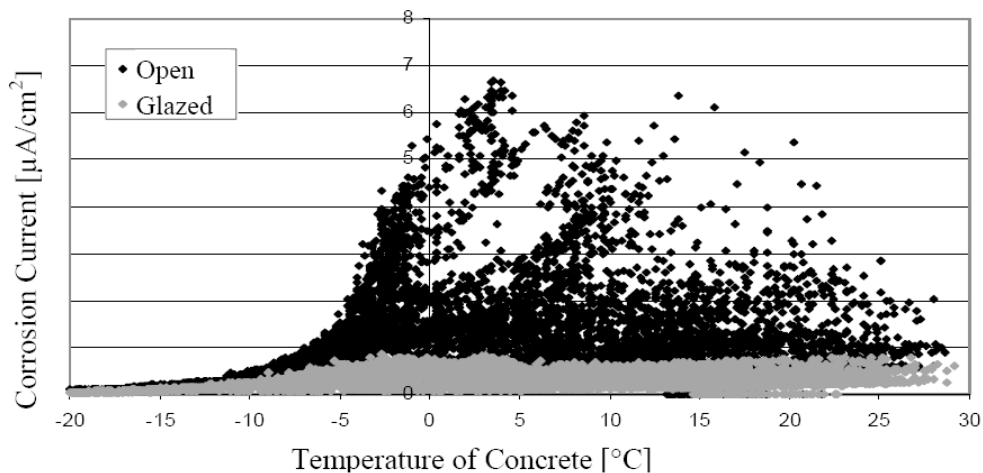


Figure 9.3. Momentary corrosion flow as a function of the concrete’s temperature at the time of the corrosion rate measurement. (from Mattila, 2003)

From figure 9.3 it can be seen that the corrosion rate in glazed balconies stops below $1 \mu\text{A}/\text{cm}^2$. Where the development of frost damage requires almost complete saturation of humidity, this means that corrosion flows at minimum 4 to $5 \mu\text{A}/\text{cm}^2$. In this way, frost damage is prevented by glazing. Upon assessment of the reliability of the results, it is important to note that the results are strongly dependent upon climate, especially on how much precipitation there has been during the monitoring period. Since the period is only a little longer than two years, the assumptions may not necessarily correspond to the long-term average conditions.

9.3 Important conclusions from Mattila’s experiment

The corrosion is measured through monitoring the corrosion rate for steel on carbonated concrete by means of sensors. On the basis of the results, Mattila has drawn the following conclusions:

- Balcony glazing extends the lifespan of balconies of reinforced concrete by reducing the humidity loading and by raising both the air’s temperature and the concrete’s temperature and thus increasing their ability to dry out.
- The lifespan is extended on the grounds of active corrosion by c. 5 years in side walls and for c. 25 years in the slabs’ underside. The latter in particular makes it possible to avoid unnecessary and difficult repairs in the lower surface of balcony slabs.
- The conditions for the development of frost damage are wholly and completely removed by glazing.

10. Conclusions

The aim of this report is to assess the effect of glazing on carbonation, reinforcement corrosion and lifespan of concrete slabs in balconies. Carbonation-initiated reinforcement corrosion and frost were regarded as the principal damage mechanisms.

The reported theoretical analyses in this report indicate that glazing has many positive effects, as follows:

- + A lower humidity loading after glazing leads to drier concrete and a significantly lower corrosion rate.
- + The lifespan increases significantly after glazing.
- + The risk of frost damage decreases due to less humidity in the concrete.
- + The interior climate in a glazed balcony is improved and the air temperature is raised by several degrees. The risk of surface condensation on concrete surfaces is thus reduced.

On the other hand, glazing has a negative effect on the following:

- The carbonation rate increases due to the concrete's lower RH, i.e. lower humidity content in capillary pores.

The measurements conducted in Finland confirm some of the above theoretical conclusions. In order to show the positive effects of balcony glazing quantitatively, measurements should be carried out. It is recommended here that both humidity and temperature in the air and concrete is measured over a sufficiently long time (at least 1 year) and in a number of reference objects with and without glazing.

An alternative way is measurement of corrosion rate by means of suitable equipment. For this purpose, one can put out a number of test bodies on balconies with and without glazing or measure the corrosion rate in the actual balcony slabs in balconies with and without glazing.

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Annexe A:

In annexe A, a calculation model for initiation time due to carbonation is shown.

Model for calculation of initiation time

Carbonation model and the included parameters are reported from Duracrete (1998). The models according to DuraCrete (1998) for initiation of reinforcement corrosion due to carbonation are the same as the "meso-model" according to CEB (1997).

$$x_{CO_2} = \sqrt{\frac{2 \cdot k_1 \cdot k_2 \cdot k_3 \cdot D_c \cdot c}{B_{CO_2}}} \cdot \sqrt{t} \cdot \left(\frac{t_0}{t}\right)^n$$

where

x_{CO_2} is the carbonation depth [m],

D_c is the diffusion coefficient for carbon dioxide [m^2/s],

c is the carbon dioxide concentration in surrounding air [$kgCO_2/m^3air$]

t is the exposure time [s],

t_0 is a reference time, the concrete's age when D_c is measured,

B_{CO_2} is the binding capacity for carbon dioxide, i.e., the volume of carbon dioxide consumed in carbonation [$kg CO_2/m^3$ concrete],

n is a climate parameter

k are parameters for consideration of climate, hardening and employed test method respectively.

As a rule, the diffusion coefficient D_c is not measured separately. Obtained from a carbonation depth measurement is the quotient B_{CO_2}/D_c also called "the effective carbonation resistance" R_{CO_2} . In order for this to be able to be used generally, all the other parameters in the model but be well-known and under control.

In fib (2004) the parameters k and n have been reformulated somewhat, to an environment factor k_e , a hardening factor k_c and an aging exponent n . The equation is then

$$x_k(t) = \sqrt{\frac{2 \cdot c_{s,ca}^k \cdot k_{e,ca}^k \cdot k_{c,ca}^k \cdot \gamma_{Rca} \cdot t \cdot (t_0/t)^{2 \cdot n_{ca}^k}}{R_{0,ca}^k}} + \Delta x$$

The initiation time can be calculated according to the equation below:

$$t(x) = \left(\frac{(x_k - \Delta x)^2 \cdot R_{0,ca}^k}{2 \cdot c_{s,ca}^k \cdot k_{e,ca}^k \cdot k_{c,ca}^k \cdot \gamma_{Rca} \cdot t_0^{2 \cdot n_{ca}^k}} \right)^{\frac{1}{1-2 \cdot n_{ca}^k}}$$

where the following is defined:

$R_{0,ca}^k$	year (kg/m ³)/mm, characteristic value of carbonation resistance, corresponding to the value of $D_{0,ca}$ as above ($R = D-1$)
t_0	year, the concrete's age upon testing, 28 d
$c_{s,ca}^k$	kg/m ³ , the carbon dioxide's surface concentration
$k_{c,ca}^k$	characteristic value for hardening factor
$k_{e,ca}^k$	characteristic value for environmental factor
n_{ca}^k	characteristic value for exponent for time dependence
x_k	covering concrete layer, mm
Δx	performance tolerance, mm
γ_{Rca}	partial coefficient for chloride penetration resistance
vbt	water-binder figure

Climate parameter values

Consideration has also been given to the fact that concrete composition and hardening vary somewhat between different parts of the constructions.

The climate parameters k_1 and n depend in part on RH in the air closest to the concrete surface, in part on the temperature, and on the duration of wet periods due to (pelting)rain, see figure A-1 and A.2, from CEB (1997).

In practice, the rain-protected parts of a concrete construction determine dimension, i.e. the air's RH at the concrete surface is the important climate parameter. In order for this to be relevant, however, the humidity must be so high that corrosion can occur when it is fully initiated, see also figure 5.2 in this report.

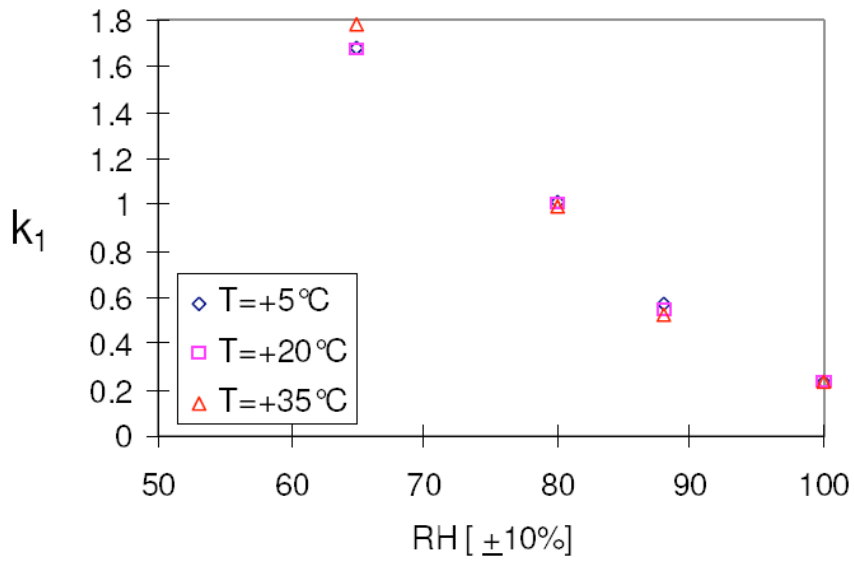


Figure A.1: The climate parameters k_1 in the carbonation model as a function of air humidity, CEB (1997)

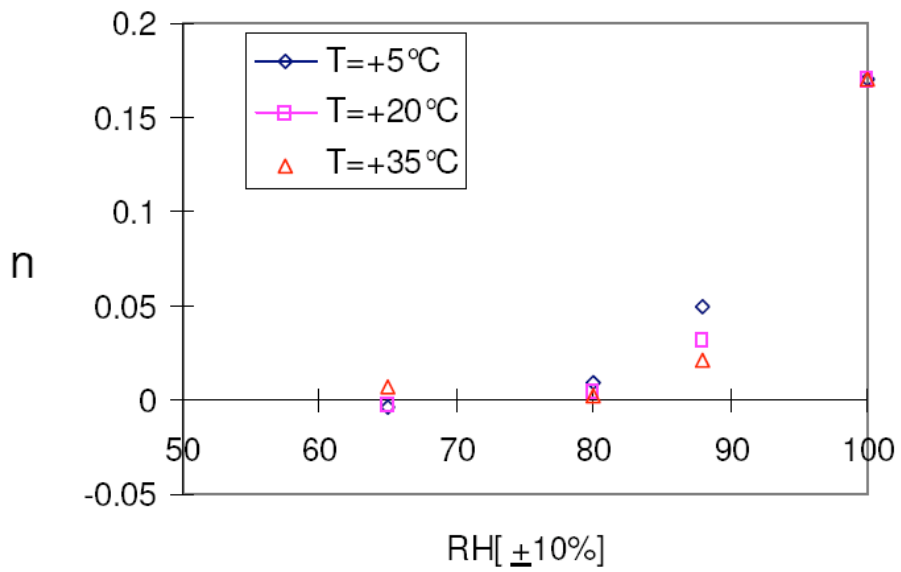


Figure A.2: The climate parameters n in the carbonation model as a function of air humidity, CEB (1997)

The model for initiation of reinforcement corrosion due to carbonation contains a large number of parameters

$$x_k(t) = \sqrt{\frac{2 \cdot c_{s,ca}^k \cdot k_{e,ca}^k \cdot k_{c,ca}^k \cdot \gamma_{Rca} \cdot t \cdot (t_0/t)^{2 \cdot n_{ca}^k}}{R_{0,ca}^k}} + \Delta x$$

Geometry:

Characteristic value for cover layer is set at the average value, or the nominal value used upon dimensioning.

Material:

It is presumed that the concrete manufacturer can state the carbonation resistance on the basis of standardised sampling method. Characteristic values are determined as 5 % fractile on the basis of the sampling result, DuraCrete (2000)

Environmental effect:

The only variable that depends solely on the environment is the carbon dioxide's surface concentration:

$$C_{c,sa}^k = 5,0 \times 10^{-4} \text{ kg/m}^3 \text{ (m}^3 \text{ air)}$$

The carbon dioxide concentration may increase.

Execution:

The hardening factor $k_{c,ca}$ depends on the hardening time according to table A.1

Table A.1: Characteristic value for factor $k_{c,ca}$ as a function of the hardening time:

Härningstid, dagar	$k_{c,ca}^k$
1	4,05
3	2,10
7	1,00
28	0,76

Härningstid, dagar	Hardening time, days.
--------------------	-----------------------

Parameters depending on material and environment:

The environment factor $k_{e,ca}$ depends on exposure and binder according to table A.2.

Table A.2: Characteristic value for the factor $k_{e,ca}$ with regard to binder and exposure. As is seen the difference due to cement type is negligible in this case.

Exponering	$k_{e,ca}^k$	
	Portlandcement (CEM I)	Slaggcement (CEM II/A-S)
Laboratorium 65 % RF	1,00	1,00
Utomhus regnskyddat	0,86	0,85
Utomhus regnutsatt	0,48	0,50

Exponering	Exposure
Portlandcement	Portland cement
Slaggcement	Slag cement
Laboratorium 65 % RF	Laboratory
Utomhus regnskyddat	Outddors rain-protected
Utomhus regnutsatt	Outdoors exposed to rain

The exponent for time dependence n_{ca} depends on exposure and binder according to table A.3.

Table A.3: Characteristic value for the exponent for time dependence n_{ca} .

Exponering	n_{ca}^k	
	Portlandcement (CEM I)	Slaggcement (CEM II/A-S)
Laboratorium 65 % RF	0	0
Utomhus regnskyddat	0,098	0,132
Utomhus regnutsatt	0,40	0,43

Exponering	Exposure
Portlandcement	Portland cement
Salggcement	Slag cement
Laboratorium 65 % RF	Laboratory
Utomhus regnskyddat	Outddors rain-protected
Utomhus regnutsatt	Outdoors exposed to rain

Recommended values of cover layer deviations and partial coefficients are given in table 7.4.

Table A.4: Cover layer deviations and partial coefficients with regard to carbonation

Relativ kostnad för reparationer		Låg	Normal	Hög
Δx	täckskiktsavvikelse (mm)	8	14	20
γ_{Rca}	karbonatiseringsmotstånd	1,30	2,10	3,00

Relativ kostnad för reparationen	Relative cost of repairs
Låg	Low
Normal	normal
Hög	High
Täckskiktsavvikelse (mm)	cover layer deviation (mm)
karbonatiseringsmotstånd	carbonation resistance

The diffusion coefficient D_c for carbon dioxide [m²/s] can be measured up on a carbonated sample of the relevant concrete either directly from a carbon dioxide flow or indirectly from oxygen gas diffusion. Measurement method for this need to be developed further and verified. The humidity dependence can be verified by taking field measurements on older constructions. Then the carbonation depth and humidity profile in the cover layer are measured simultaneously.

As a rule, the diffusion coefficient D_c or the volume of lime capable of carbonation B_{CO_3} are not measured separately. The quotient D_c/B_{CO_1} as a resistance R_{ca} is obtained from a carbonation depth measurement. In order for this to be able to be used generally, all the other parameters in the model must be well-known and under control. This is suitably done in a laboratory testing with constant surrounding conditions and raised carbon dioxide concentration, i.e. in an accelerated carbonation testing.

The environmental factor k_e and aging exponent n can be assessed through field measurements on older constructions. The aging factor requires measurement of the same part of a construction on at least two occasions which are relatively well separated in time.

The environmental factor can be quantified through comparative measurements of different parts of one and the same construction where the climate loading has been different. The humidity conditions in the concrete are then also documented. Since such parts probably also have different aging factors, it is difficult to quantify the environmental factor separately from measurement on only one occasion.

The hardening factor k_c is difficult to determine experimentally in a relevant manner. The traditional method is to harden concrete sample bodies in different ways and then carbonate them over a number of years with accelerated

carbonation at raised carbon dioxide concentration. Through comparison between the different carbonation depths, the hardening factor k_c can be determined.

The hardening factor determined in this way then applies to the relevant testing period. For longer exposure times, i.e. long lifespans, the factor will be smaller and smaller since deficient hardening mostly affects the outer parts of the concrete.

Annexe B:

In annexe B the calculation model for cover layer splitting on the basis of reinforcement corrosion during a propagation period, is accounted.

The cover layer splitting's dimensioning conditions

The dimensioning condition is based on the criterion that the dimensioning value w^d achieves its critical value w_{cr} .

$$g = w_{cr} - w^d \geq 0$$

Dimensioning values

Crack breadth:

The crack breadth's dimensioning value can be estimated on the basis of the following expression, determined through regression analysis:

$$w^d = w_0 \quad \text{om} \quad p_0 \leq p^d$$

$$w^d = w_0 + b^d (p^d - p_0) \quad \text{om} \quad p_0 > p^d$$

where

w_0 the visible crack's breadth

b^d dimensioning value for parameters that depend on the reinforcement rod's positioning

p^d dimensioning value for relevant rust attack depth in μm

p_0^d dimensioning value for the penetration in μm that initiates cracking

Dimensioning value for the rust attack depth that initiates cracking:

A possible corrosion affects the construction in two ways:

Adhesion reduces due to splitting forces and also gives rise to lower lever arm on the pressured side of concrete constructions.

The reinforcement's area diminishes in the event of corrosion.



Korrosion av armering	Corrosion of reinforcement
Ökande volym	Increasing volume
Armeringens area minskar	Reinforcement's area decreases
Spjälkkrafter	Splitting forces
Vidhäftningen påverkas	Adhesion affected
Inre hävarmen minskar	Innerer Hebel wird kleiner

Figure B.1: Corrosion of reinforcement and its effect on construction

The following formula can be used for calculation of the dimensioning value of the rust attack depth initiating cracking, p_0^d .

$$p_0^d = a_1 + a_2 \frac{x^d}{d} + a_3 f_{c,sp}^d$$

where

a_1, a_2, a_3 regression coefficients

x^d dimensioning value of cover layer

d rod diameter

$f_{c,sp}^d$ dimensioning value of the concrete's breaking strain in MPa

Alternatively, the dimensioning value of p_0^d can be read off from the figure below.

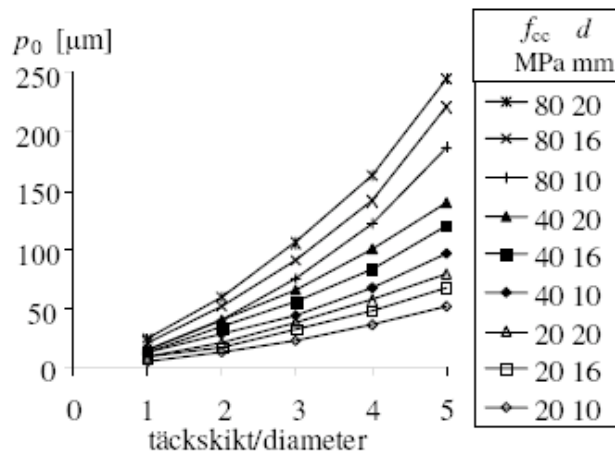


Figure B.2: Corrosion depth that cracks the cover layer (p_0^d) depending on cover layer, diameter of reinforcement rod and concrete, for max. stone size 16 mm.

Relevant rust attack depth after the time, t:

$$p^d = 0 \quad \text{om } t \leq t_i^d$$

$$p^d = V^d \cdot w_t \cdot (t - t_i^d) \quad \text{om } t > t_i^d$$

where

V^d dimensioning value for corrosion rate

w_t relative length of wet periods when the concrete has RH \geq 85%

t_i^d dimensioning value for the time until corrosion initiation

Dimensioning value for corrosion rate

$$V^d = \frac{m_0}{\rho^k} \cdot \alpha^k \cdot F_{cl}^k \cdot \gamma_V$$

Where

m_0 constant in the correlation corrosion rate - resistivity

F_{cl}^k characteristic value of factor for chloride corrosion rate

α^k characteristic value of factor for pitting

- ρ^k characteristic value for resistivity
 γ_V partial coefficient for corrosion rate

Characteristic value for resistivity:

$$\rho^k = \rho_0^k \cdot \left(\frac{t_{hydr}}{t_0} \right)^{n_{res}^k} \cdot k_{c,res}^k \cdot k_{T,res}^k \cdot k_{RH,res}^k \cdot k_{cl,res}^k$$

- ρ_0^k characteristic value for the potential electrolytic resistivity
 t_0 the concrete's age at the time of acceptance testing
 t_{hydr} the concrete's actual age, though a maximum of 1 year is credited
 n_{res}^k characteristic value of the resistivity's exponent for time dependence
 $k_{c,res}^k$ characteristic value for the resistivity's hardening factor
 $k_{T,res}^k$ characteristic value for the resistivity's temperature factor
 $k_{RH,res}^k$ characteristic value for the resistivity's humidity factor
 $k_{cl,res}^k$ characteristic value for the resistivity's chloride factor

$$k_{T,res}^k = \left(1 + K^k (T - 20) \right)^1$$

- K^k characteristic value for a factor that describes the resistivity's temperature dependence
 T temperature in °C

Time to corrosion initiation:

Depending on whether it is a question of chloride-initiated or carbonation-initiated corrosion, the time can be determined by means of different calculations.

Parameters that consider the reinforcement's position in cross-section:

$$b^d = b^k \cdot \gamma_b$$

where

- b^k characteristic value
 γ_b partial coefficient

The concrete's breaking strain:

For the concrete's breaking strain, the characteristic value such as dimensioning value is employed in this context.

$$f_{c,sp}^d = f_{c,sp}^k$$

Characteristic values

Geometry:

Characteristic value for cover layer is set at the nominal value employed upon dimensioning, or average value if it is a question of measured values

Material:

The potential electrolytic resistivity ρ_0 is used as a variable that determines the resistance capacity with characteristic value defined as 5 % fractile. It is presumed that the concrete manufacturer can state the resistivity on the basis of some standardised testing method, e.g. Two Electrode Method (TEM).

Characteristic breaking strain f_{ctk} for the concrete is defined as 5 % fractile according to relevant standard, such as BBK 04 or Eurocode 2 (EN 1992-1-1). The exponent for time dependence n_{res} is given in the following table:

Table B.1: Exponent for time dependence with regard to resistivity:

Cement type	n_{res}^k
Portland cement (CEM I)	0.23
Slag cement (CEM II/A-S)	0.54
Fly gas cement (CEM II/A-V, II/B-V)	0.62

Environmental effect:

Temperature and relative humidity are defined as annual average values and can be determined by the use of meteorological data for the relevant location.

In the following tables the values are given for the factor for chloride corrosion rate F_{cl} , relative length of wet periods w_t , the temperature factor K , the factor for pitting, a , and the resistivity's chloride factor $k_{cl,res}$.

Table B.2: Characteristic values for the factor for chloride corrosion rate, F_{cl} .

Occurrence of chlorides	F_{cl}^k
Yes	2.63
No	1.0

Table B.3: Characteristic values for relative length of wet periods (when the concrete has RH \geq 85 %).

Humidity conditions	w_f
Dry, alternatively moderately humid, protected	0
Airborne seawater	0.5
Cyclical wet and dry, unprotected against rain/seawater	0.75
Wet, rarely dry, tidewater zone	1.0

Table B.4: Characteristic values for temperature factor K.

Temperature	K_k
< 20°C	0.025
> 20°C	0.073

Table B.5: Characteristic values for factor for pitting, a.

Occurrence of chlorides	a^k
Yes	9.28
No	2.0

Table B.6: Characteristic values for the resistivity's chloride factor $k_{cl,res}$.

Occurrence of chlorides	$k_{cl,res}^k$
Yes	0.72
No	1.0

Execution:

Characteristic value for resistivity's hardening factor $k_{c,res}$ is set at $k_{c,res} = 1.0$.

Parameters depending on material and environment:

Values for resistivity's humidity factor $k_{RH,res}$ are given in the following table.

Table B.7: Characteristic value for resistivity's humidity factor $k_{RH,res}$.

Humidity conditions	$k_{RH,res}^k$	
	Portland cement, (CEM I)	Slag cement, (CEM IIA/-S)

Unprotected	1.44	1.44
50 % RH	7.58	14.7
65 % RH	6.45	7.00
80 % RH	3.18	3.80
95 % RH	1.08	1.17
Constantly under water	1.0	1.0

Other parameters:

Table B.8: Characteristic values for other parameters are given in the following table:

Parameter	Characteristic value	Unit
w_0	0.05	mm
w_{cr}	1.0	mm
a_1	74.4	μm
a_2	7.3	μm
a_3	17.4	$\mu\text{m}/\text{MPa}$
b	upper edge: 0,0086 under edge: 0,0104	mm/ μm
m_0	882	mm $\times\Omega\text{m}/\text{year}$

Partial coefficients

For chloride initiated corrosion the partial coefficients γ_b and γ_v can always be set as equalling 1.0, since the propagation phase contributes insignificantly to the lifespan. For carbonation initiated corrosion, the propagation phase has greater importance, the values of the partial coefficients γ_b and γ_v are therefore given in the following table.

Table B.9: The partial coefficients γ_b and γ_v for carbonation initiated corrosion.

Relative cost of repairs	Low	Normal	High
γ_b	1.30	1.40	1.55
γ_v	1.30	1.40	1.50